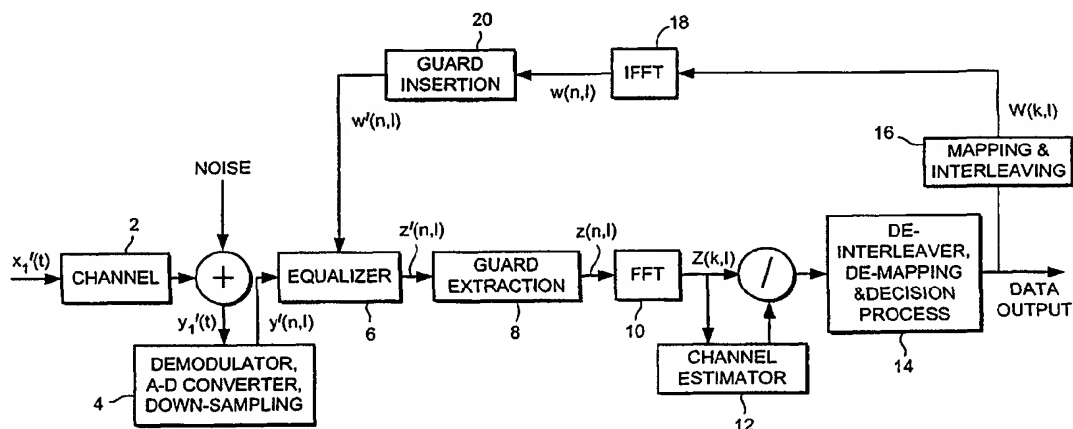




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(21) International Application Number: PCT/GB00/00174 (22) International Filing Date: 24 January 2000 (24.01.00) (30) Priority Data: 9901491.2 22 January 1999 (22.01.99) GB (71) Applicant (for all designated States except US): UNIVERSITY OF BRISTOL [GB/GB]; Senate House, Tyndall Avenue, Bristol BS8 1TH (GB). (72) Inventors; and (75) Inventors/Applicants (for US only): ARMOUR, Simon [GB/GB]; 689 Wellsway, Odd Down, Bath BA2 2TZ (GB). BULL, David, Roger [GB/GB]; Netherways, Netherhope Land, Tidenham, Chepstow, Monmouthshire NP16 7JE (GB). NIX, Andrew, Robert [GB/GB]; 7 Bellview, Clifton, Bristol BS8 1DA (GB). (74) Agent: O'CONNELL, David, Christopher; Haseltine Lake & Co., Imperial House, 15-19 Kingsway, London WC2B 6UD (GB).		(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG). Published <i>With international search report.</i>

(54) Title: OFDM RECEIVER WITH ADAPTIVE EQUALISER



(57) Abstract

An OFDM receiver includes an adaptive equalizer, which acts on a received signal, after conversion to digital samples. After filtering by the equalizer, any guard interval is removed, and a Fast Fourier Transform is applied to the signal. The data signal is then estimated and the estimated data is supplied as an output. The estimated data also has any guard interval reinserted, and is applied to an Inverse Fast Fourier Transform, and is fed back to the equalizer to allow adaptation of the tap coefficients thereof.

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OFDM RECEIVER WITH ADAPTIVE EQUALISER

This invention relates to a receiver, and in particular to an OFDM receiver, and to an adaptive equalizer for use in such a receiver and to a method of training the equalizer.

The European digital terrestrial television standard, DVB-T, specifies orthogonal frequency division multiplexing, OFDM as the modulation scheme.

In conventional OFDM systems, multipath radio transmission channels cause delay spread distortion of the transmitted signal. Although adaptive equalizers can be used in many applications to cancel out delay spread distortion, existing designs for OFDM receivers and adaptive equalizers are generally incompatible, although it has been proposed to use a number of equalizers acting in parallel on respective sub-bands of the OFDM signal.

Therefore, existing designs for OFDM systems employ guard intervals to combat the effects of delay spread. Each transmission period includes a period during which useful information is transmitted, and a guard interval, during which no useful information is transmitted. Thus, use of a guard interval reduces efficiency of the transmission, and less data can be transmitted within a given radio frequency bandwidth.

The present invention relates to an OFDM receiver including an adaptive equalizer, which attempts to overcome the incompatibility of existing designs of OFDM receivers and adaptive equalizers.

According to a first aspect of the present invention, there is therefore provided a receiver as defined in claim 1.

According to a second aspect of the present invention, there is therefore provided an equalizer as defined in claim 6.

According to a third aspect of the present invention, there is therefore provided a method as defined in claim 7.

For a better understanding of the present invention, reference will now be made to the
5 accompanying drawings, in which:-

Figure 1 shows a first receiver in accordance with the invention;

Figure 2 shows a first equalizer in accordance
10 with the invention;

Figure 3 shows a second equalizer in accordance with the invention;

Figure 4 shows a second receiver in accordance with the invention.

15 **DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS**

As Shown in Figure 1, a transmitted analog OFDM symbol is received over a radio frequency channel 2 having unknown and time-varying characteristics, and is subject to the addition of noise.

20 The receiver therefore takes an input signal $y_1'(t)$ in an input device 4, where it is demodulated, A-D converted and down-sampled to give a time domain vector $y'(n,1)$. The received sequence $y'(n,1)$ is filtered by an adaptive equalizer 6 to produce a time-domain
25 sequence $z'(n,1)$.

The time domain sequence output from the equalizing filter 6 is input to a guard extraction device 8 to form an output $z(n,1)$. An advantage of the present invention is that the need for a guard interval
30 may be reduced or eliminated. The guard extraction device 8 is therefore required only if it is needed if a guard interval is used by the transmitter which is in use.

A Fast Fourier Transform (FFT) 10 is then applied
35 to $z(n,1)$ to produce a frequency domain vector $Z(k,1)$.

In this embodiment of the invention, the frequency

domain vector is supplied to a channel estimator 12 which derives an estimation of the radio channel's frequency response and compensates according to this estimate. In an alternative embodiment, the channel estimator may be omitted.

The vector is then supplied to an output device 14 to produce a data output. The output device 14 may be nothing more than a hard limiter, putting the data into a useable form. However, any interleaving, coding, signal mapping or other error control strategies applied in the transmitter are reversed in the output device 14 and exploited to correct any errors and produce the output data sequence. The output data, which is the best possible estimate of the data content of the transmitted signal is then applied to a feedback loop, and processed to form the best possible estimate of the transmitted sequence. Specifically, the data output is applied to a device 16 which interleaves, codes and maps the data in an identical manner to that performed at the transmitter to produce the frequency domain sequence $W(k,l)$.

The frequency domain sequence is input to an inverse Fourier transform device 18 and the output $w(n,l)$ of this device is applied to a guard interval insertion device 20 to insert a guard interval corresponding to any that was added in the transmitter to generate a sequence $w'(n,l)$. In effect, the data output is processed in the feedback loop to effectively attempt to reconstruct the OFDM symbol that was generated at the transmitter, and hence $w'(n,l)$ is an estimate of the transmitted sequence $x'(n,l)$.

The estimate $w'(n,l)$ is then input to the equalizing filter 6 to enable decision directed adaptation of the tap coefficients thereof.

Each updated estimate of an OFDM symbol, made up of a number of sub-symbols, is available to the

equalizer only after all sub-symbols of one OFDM symbol have been received.

Figure 2 shows the equalizer of the present invention. As is generally conventional, the equalizer consists of two shift register sections: a feedforward section 32 that stores future transmission symbols and the current transmission symbol and a feedback section 34 that stores previous transmission symbols. The length of the feedforward section is (J_1+1) symbols and the length of the feedback section is J_2 symbols. The received sequence $y'(n,l)$ is input, the value of each stored symbol is multiplied by a tap coefficient $c(j)$, and the results are summed to form the equalizer output $z'(n,l)$.

The tap coefficients $c(j)$ are updated according to the LMS adaptation algorithm. As is known, the LMS algorithm adapts the equalizer taps according to the error measure between the equalizer output symbols and an estimate of the transmitted symbols. The estimate of the transmitted symbols can be achieved either by means of a training sequence or by decision directed adaptation.

Adaptation according to a training sequence requires the transmission of symbols of which the equalizer has prior knowledge. This training mode allows adaptation according to an error free estimate of transmitted symbols but results in no data throughput.

Decision directed adaptation feeds back output data to estimate the transmitted symbols. This estimate is not necessarily error free but does allow for data throughput.

In practice, the two techniques are combined. An initial training sequence approximately adapts the equalizer and reduces equalizer output error sufficiently that decision directed adaptation may

provide an adequate error measurement for further adaptation. During decision directed adaptation the equalizer further adapts both to 'fine tune' its action and to track any relatively small time variation in the radio channel.

The equalizer of Figure 2 is generally similar to a conventional equalizer, although there are differences as follows:-

Symbols input to the feedback register 32 during decision directed operation do not come directly from the decision device but rather from the feedback vector.

Symbols used to calculate error during decision directed operation come similarly from the feedback vector rather than direct from the decision device.

Additional buffers 36, 38 for both feedforward and feedback sections further store past symbols beyond the duration of the feedforward/feedback sections. These additional stored values are required for decision directed adaptation

During decision directed mode the tap coefficients are not updated at intervals of the sub-symbol period, but rather at the OFDM symbol period, regarding one OFDM symbol as made up a group of sub-symbols.

However, the LMS calculation is performed in the LMS calculation processor 40 to calculate adjustments corresponding to intervals of the sub-symbol period with the sum of all calculated adjustments being made at intervals of the OFDM symbol period.

The equalizer output may be directly input to the feedback section thereof.

These additional features, which apply during a decision directed (or data derived) operation, enable the equalizer to operate within the OFDM receiver architecture.

More detailed explanation of all these features is

given below.

Since the equalizer operates on the received time domain sequence its output is also a time domain sequence. Data in the OFDM modem is in the frequency domain and hence the equalizer output must be Fourier Transformed (with any guard interval first being removed) prior to the decision process. Thus, the output of the equalizer cannot be applied directly to the decision device. Similarly the decision device output cannot be fed back directly to the equalizer. The feedback vector is fed back instead. If the equalizer is adapting according to a training sequence this is irrelevant, since the training sequence itself is an error free estimate of the transmitted sequence and can be input to the equalizer's feedback section. Furthermore, the decision device output cannot be used to calculate the output error used in the LMS adaptation algorithm and the feedback vector is again used instead.

The additional symbol buffering and the changes to the adaptation process in decision directed mode are necessary since the parallel transmission undertaken in OFDM results in the group post-decision data sub-symbols making up one OFDM symbol being simultaneously output at intervals of the OFDM symbol period. (By contrast, a single carrier system outputs individual symbols at intervals of the symbol period.) This restriction imposed by the parallel transmission prevents decision directed adaptation during OFDM symbols. It also prevents feedback values becoming available to the equalizer until the end of the OFDM symbol.

Therefore, instead of adapting the equalizer with each transmission sub-symbol, all transmission symbols forming the OFDM symbol are clocked through the equalizer with the tap coefficients remaining constant

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and the equalizer output is input directly into the feedback section. At the end of each OFDM symbol the past and future transmission symbols that were stored in the feedforward and feedback sections at the start of the OFDM symbol are recovered from the buffers.

5 Since the tap coefficients remain constant throughout the OFDM symbol the equalizer is effectively returned to its state at the start of the OFDM symbol. The OFDM symbol is then clocked into the equalizer once more

10 with the feedback OFDM symbol now available both for determination of error and input to the feedback section. This process enables the adaptation steps that had not previously taken place to be completed and replaces the fed back output symbols with post decision

15 estimates of the transmitted symbols as provided by the feedback OFDM symbol.

This method of operation described above allows both the feedforward and feedback stages of the equalizer to have numbers of taps which are integer

20 multiples of the length of the extended OFDM symbol, which is considered to be $(N+M)$, with N the number of transmission symbols in the useful period of an OFDM symbol, and M the number of transmission symbols in the guard period. In this illustrated embodiment, these

25 numbers of taps are equal to the length of the extended OFDM symbol.

The equalizer output is then given by:-

$$z'(n,l) = \sum_{j=-J_1}^{-J_1+n} c(j) y'((n-j-(N+M)), l+1) + \sum_{j=-J_1+n+1}^0 c(j) y'((n-j), l) \\ + C_{out}(n) \sum_{j=1}^n c(j) z'((n-j), l) + \sum_{j=n+1}^{J_2} c(j) w'((n+(N+M)-j), l-1)$$

where:

$$C_{out}(n) = 0 \quad \text{for} \quad n = 0$$

and:

$$C_{out}(n) = 1 \quad \text{for} \quad n \neq 0$$

The equalizer is then adapted according to the LMS algorithm, which in this case is defined as follows:-

During Training Mode:

$$c(j, n+1, l) = c(j, n, l) + \Delta \varepsilon'(n, l) y^{**}((n-j-(N+M)), l+1)$$

$$\text{for } -J_1 \leq j \leq -J_1 + n + 1$$

$$c(j, n+1, l) = c(j, n, l) + \Delta \varepsilon'(n, l) y^{**}((n-j), l)$$

$$\text{for } -J_1 + n + 2 \leq j \leq 0$$

$$c(j, n+1, l) = c(j, n, l) + \Delta \varepsilon'(n, l) x^{**}((n-j), l)$$

$$\text{for } 1 \leq j \leq n$$

$$c(j, n+1, l) = c(j, n, l) + \Delta \varepsilon'(n, l) x^{**}((n+(N+M)-j), l-1)$$

$$\text{for } n+1 \leq j \leq J_2$$

$$\varepsilon'(n, l) = x'(n, l) - z'(n, l)$$

During Decision Directed Operation

$$c(j, n, l+1) = c(j, n, l) + C_F(j) \sum_{n=0}^{N+M+j-1} \Delta \varepsilon'(n, l) y'((n-j), l) + \sum_{n=N+M+j}^{N+M-1} \Delta \varepsilon'(n, l) y'((n-(N+M)-j), l+1)$$

$$\text{for } -J_1 \leq j \leq 0$$

$$c(j, n, l+1) = c(j, n, l) + \sum_{n=0}^{j-1} \Delta \varepsilon'(n, l) w'((n+(N+M)-j), l-1) + C_F(j) \sum_{n=j}^{N+M-1} \Delta \varepsilon'(n, l) w'((n-j), l)$$

$$\text{for } 1 \leq j \leq J_2$$

$$\varepsilon'(n, l) = w'(n, l) - z'(n, l)$$

where:

$$C_f(j) = 0 \quad \text{for} \quad -j = N + M$$

and:

$$C_f(j) = 1 \quad \text{for} \quad -j \neq N + M$$

5

$$C_f(j) = 0 \quad \text{for} \quad j = N + M$$

and:

$$C_f(j) = 1 \quad \text{for} \quad j \neq N + M$$

10

Δ Equalizer step constant

$c(j, n, l)$ Equalizer tap vector in OFDM system

$\varepsilon(n, l)$ Equalizer output error vector in OFDM system

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Figure 3 shows an alternative equalizer in accordance with the invention. It corresponds generally to that of Figure 2, except that the symbols input to the equalizer's feedback section 34 are zero symbols. This prevents the feedback of noise bearing symbols into the equalizer but, as a consequence, the equalizer no longer cancels delay spread distortion from within the same OFDM symbol. However this will still allow for an effective transmission strategy since, for example, where a guard interval is employed, delay spread interference within the same OFDM symbol does not cause inter-carrier interference (ICI). Thus, an equalizer with zero symbol feedback may be combined with a channel estimation process to achieve cancellation of delay spread distortion without the need to feed back pre-decision transmission symbols.

Thus, in Figure 3, compared with Figure 2, the feedback path from the equalizer output directly to the feedback section is replaced by a zero symbol source.

The equalizer output then becomes:-

$$C_{out}(n) = 0, \text{ for all } n.$$

The method of tap adaptation in the equalizer of figure 3 is the same as that described above with reference to Figure 2.

The equalizer is no longer required to cancel all delay spread distortion and hence the equalizer output is not expected to approximate the transmitted sequence. The receiver is therefore as shown in Figure 4, as the feedback vector must be adjusted to compensate the uncombatted distortion. This is achieved by reversing the channel compensation process in the feedback path. Thus the channel estimate produced by the channel estimator 12 is applied in reverse to the output of mapping and interleaving device 16. This achieves a feedback vector which is suitably adjusted.

There is thus described a receiver, and an equalizer, which allow adaptive equalization of OFDM signals, with a consequent improvement in the noise in the received signals.

CLAIMS

1. An OFDM receiver, comprising:
a received signal processor, for demodulating, A-D
5 converting, and down-sampling received signals to form
a time domain digital signal vector;
an equalizer, having at least a feedback section
and having a plurality of tap coefficients, the
equalizer acting on the time domain digital signal
10 vector to form a filtered time domain sequence;
a Fast Fourier Transform processor, for acting on
the filtered time domain sequence to form a frequency
domain vector;
an output device, for converting the frequency
15 domain vector into an output data signal;
an inverse Fast Fourier Transform processor, for
acting on the output data signal to form an estimate of
the transmitted sequence;
wherein the estimate of the transmitted sequence
20 is supplied as an input to the equalizer to enable
decision directed adaptation of the tap coefficients
thereof, and further as an input to the feedback
section of the equalizer.
2. An OFDM receiver as claimed in claim 1,
25 further comprising:
a guard extraction device, for extracting any
guard sequence from the filtered time domain sequence
before processing by the Fast Fourier Transform
processor; and
30 a guard insertion device, for inserting a guard
interval, corresponding to that removed by the guard
extraction device, into the estimate of the transmitted
sequence supplied by the inverse Fast Fourier Transform
processor.
3. An OFDM receiver as claimed in claim 1,
35 further comprising:

a channel estimator, for compensating the frequency domain vector to produce a compensated frequency domain vector.

4. An OFDM receiver as claimed in claim 1,
5 wherein the output device comprises means for exploiting and cancelling any error control strategies applied in a transmitter of the received signals, and further comprising:

means for reapplying to the output data signal any
10 error control strategies cancelled in the output device.

5. An OFDM receiver as claimed in claim 4,
wherein the output device comprises means for deinterleaving the compensated frequency domain vector.

15 6. An OFDM receiver as claimed in claim 4,
wherein the output device comprises means for demapping the compensated frequency domain vector.

7. An adaptive decision feedback equalizer,
comprising:

20 a first input, for a received signal comprising a plurality of symbols, the symbols representing an OFDM signal, each OFDM symbol comprising a plurality of sub-symbols per OFDM symbol period;

a feedforward stage, comprising a first number of
25 taps and corresponding tap coefficients;

a feedback stage, comprising a second number of
taps and corresponding tap coefficients;

a first buffer, for storing past symbols beyond
symbols present in the feedforward stage;

30 a second buffer, for storing past symbols beyond
symbols present in the feedback stage;

a correction algorithm processor, for updating tap
coefficients of taps in the feedback stage and the
feedforward stage at intervals of the OFDM symbol
35 period.

8. A method of adapting coefficients of an

adaptive equalizer, the equalizer comprising:

a first input, for a received signal comprising a plurality of symbols, the symbols representing an OFDM signal, each OFDM symbol comprising a plurality of sub-symbols per OFDM symbol period;

a second input, for receiving a feedback signal comprising an estimate of a transmitted signal;

a feedforward stage, comprising a first number of taps and corresponding tap coefficients;

a feedback stage, comprising a second number of taps and corresponding tap coefficients;

a first buffer, for storing past symbols beyond symbols present in the feedforward stage;

a second buffer, for storing past symbols beyond symbols present in the feedback stage; and

a correction algorithm processor, for updating tap coefficients of taps in the feedback stage and the feedforward stage at intervals of the OFDM symbol period, the method comprising:

supplying the feedback signal to the second input once per symbol period;

calculating required corrections to the tap coefficients corresponding to intervals of the sub-symbol period; and

updating the tap coefficients of the taps at intervals of the OFDM symbol period based on all calculated corrections obtained during each said period.

9. A method as claimed in claim 8, further comprising outputting an equalized signal at intervals of the symbol period.

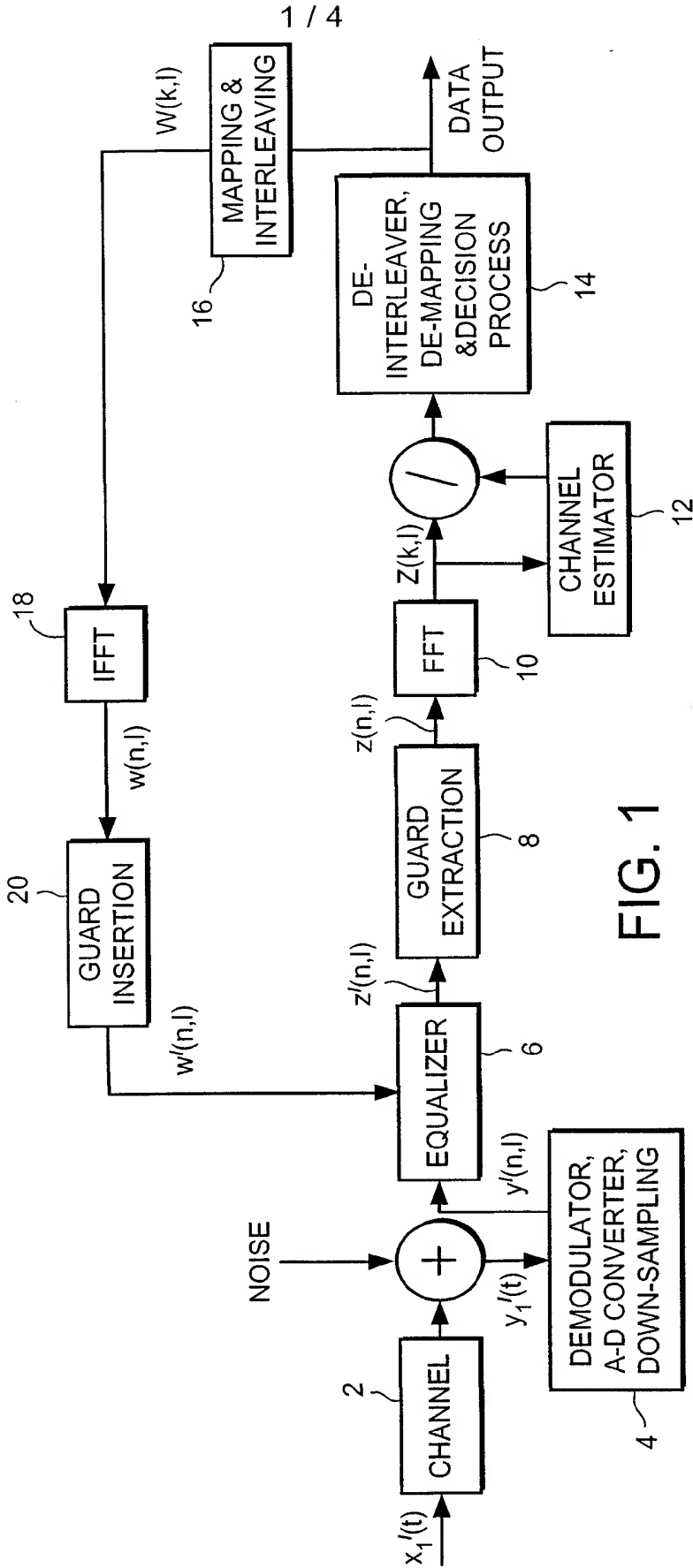


FIG. 1

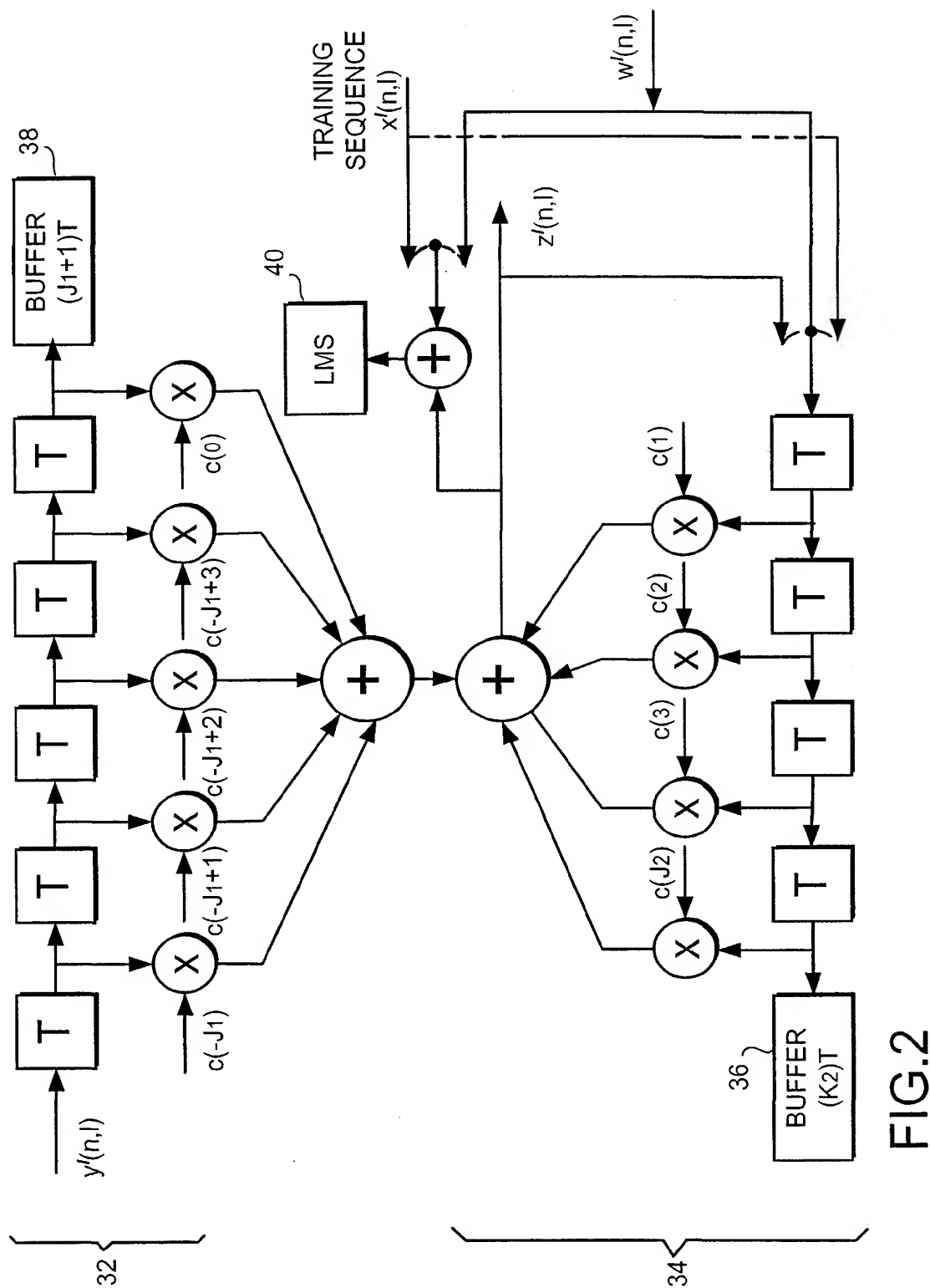


FIG. 2

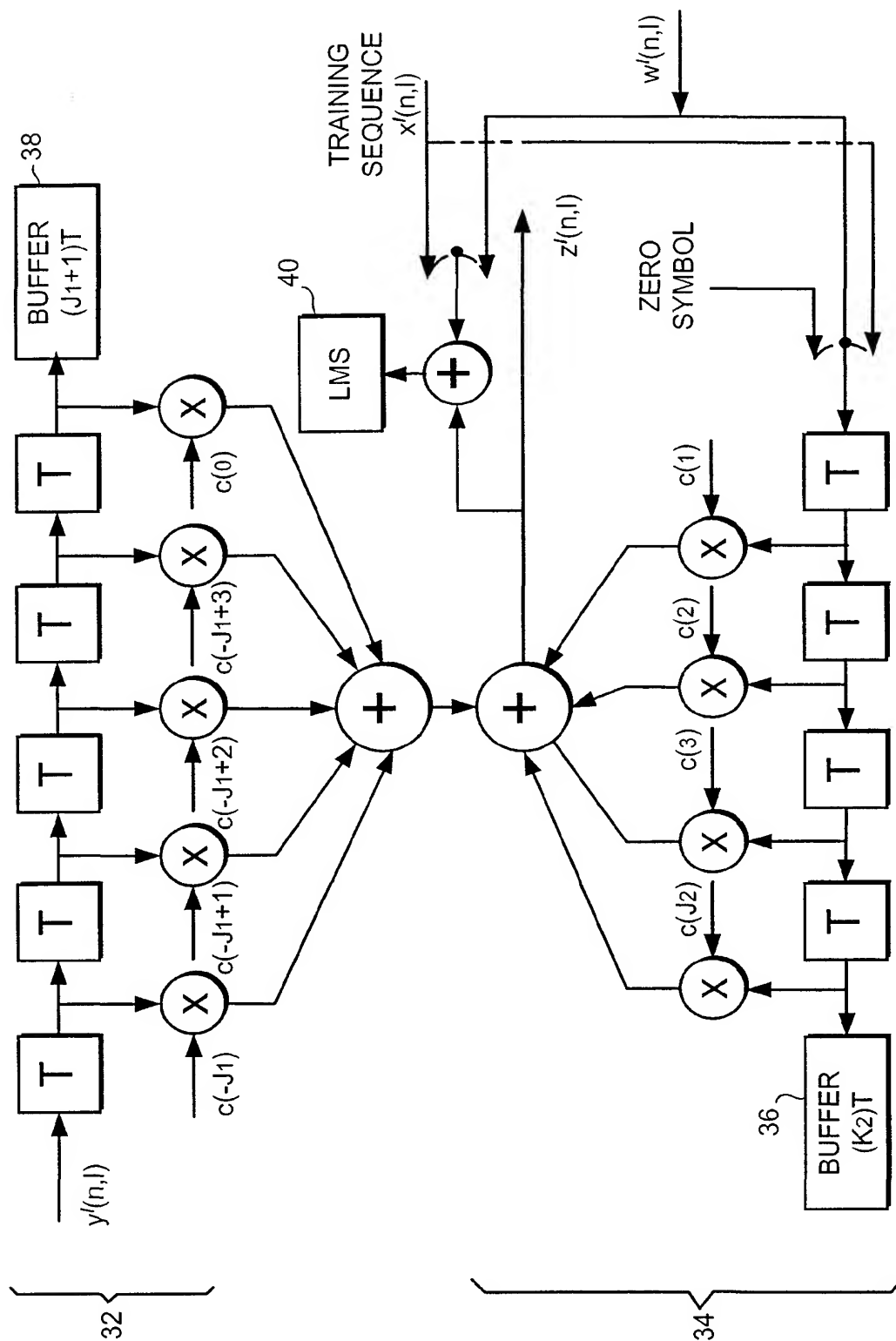


FIG. 3

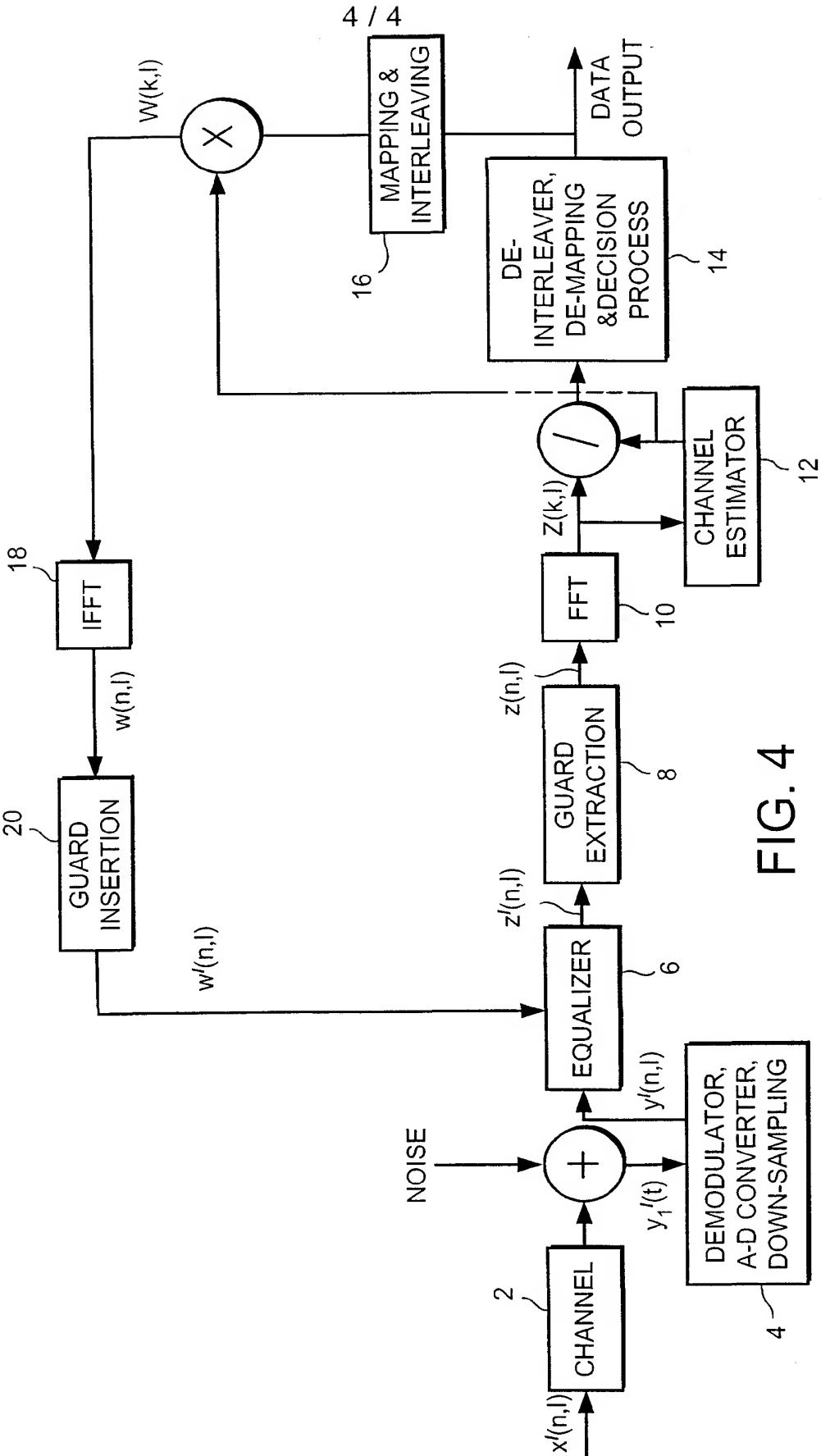


FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 00/00174

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04L27/26 H04L25/03

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	EP 0 797 333 A (TELEDIFFUSION FSE ;FRANCE TELECOM (FR)) 24 September 1997 (1997-09-24) abstract page 5, line 29 -page 6, line 46; figure 3 ----	1-9
A	US 5 285 474 A (CHOW JACKY ET AL) 8 February 1994 (1994-02-08) ----- -/--	1-9



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

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Date of the actual completion of the international search

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Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Koukourlis, S

INTERNATIONAL SEARCH REPORT

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	<p>ARMOUR S ET AL: "Pre-FFT equaliser design for OFDM"</p> <p>ELECTRONICS LETTERS, vol. 35, no. 7, 1 April 1999 (1999-04-01), pages 539-540, XP002135846</p> <p>UK ISSN: 0013-5194 the whole document</p> <p style="text-align: center;">---</p>	1-9
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

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